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Doppler Broadening as a Lower Limit to the Angular Resolution of Next Generation Compton Telescopes

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Abstract

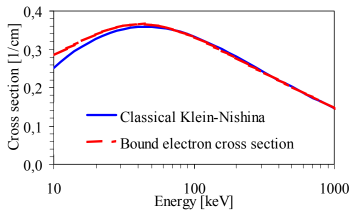
The angular resolution of a telescope which detects gamma-rays via the Compton effect is fundamentally limited below a few hundred keV by the fact that the target electrons have an indeterminable momentum inside their atoms. This additional component in the energy and momentum equation results in a Doppler broadening of the angular resolution compared to the standard Compton equation for a target at rest. The deterioration in resolution is most pronounced for low photon energy, high scatter angle, and high Z of the scatter material. This physical limit to the angular resolution of a Compton telescope is present even if all other parameters (e.g. energy and position) are measured with high accuracy.

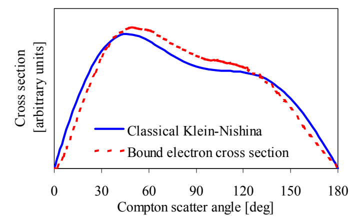
Introduction

With the development of the next generation of Compton telescopes, which will cover a larger energy band and provide much better energy resolution than their predecessor COMPTEL, the angular resolution is slowly converging towards its lower limit, which is determined by the momentum distribution of the bound electrons in the scatter material.

Comparing the classic Compton scattering process, where the electron is assumed to be at rest, with the bound electron Compton process, three consequences arise:

- The total scatter probability changes: Especially at lower energies, photons have a slightly higher probability to scatter than predicted by the Klein-Nishina equation (see Fig. **Right Top**).
- The scatter angle distribution changes: Compared to the Klein-Nishina equation small and large scatter angles are slightly suppressed. This effect is reduced for higher energies (see Fig. **Right Bottom** for 100 keV).
- The energy distribution between recoil electron and scattered gamma-ray changes. As a consequence the measured scatter angle and the one calculated with the standard Compton equation differ, which leads to broadened lines in the energy spectra for fixed scatter angles. Therefore this effect is widely known as Doppler broadening.





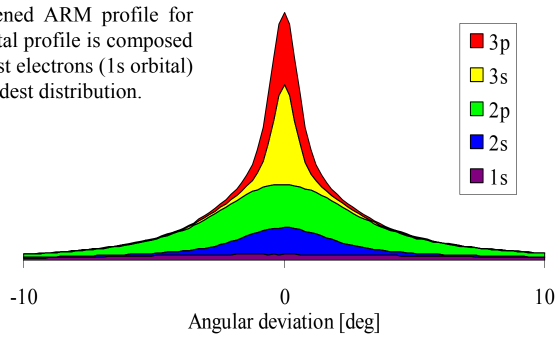
Whereas the first two points have little impact on the design of Compton scattering-based telescopes, the changed energy distribution, due to the undeterminable momentum of the electron, gives rise to a lower limit of the angular resolution.

All following results were obtained by simulations with a modified version of the GEANT3 Low Energy Compton Scattering (GLECS v3.2) package by Marc Kippen. From now on we assume ideal detectors, which have absolute accuracy in their measurement of energy and position. Moreover, all photons are completely absorbed within the sensitive detector material and all background events can be rejected.

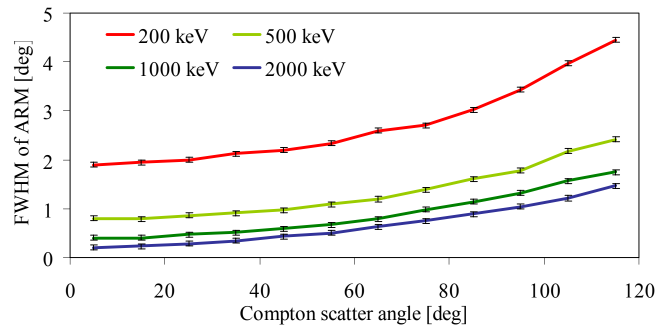
Angular resolution profiles

The angular resolution of a Compton telescope is the FWHM of the Angular Resolution Measure (ARM): It is the difference between the geometrical scatter angle (angle between the direction of the initial and the scattered photon) and the scatter angle calculated with the Compton equation via the energies of electron and gamma-ray.

An example for the shape of a Doppler-broadened ARM profile for silicon is shown in the figure on the right. The total profile is composed of the profiles of the different shells: the innermost electrons (1s orbital) have the highest momentum, and therefore the widest distribution. The 2p orbital is populated by six electrons, whereas all other orbitals consist of two electrons. For this reason the 2p orbital contributes most to the width of the profile. The outermost electrons have the lowest momentum and therefore form the peak of the distribution. **This lower limit to the angular resolution is present even if all other parameters (energy, position) are measured with ideal accuracy!**

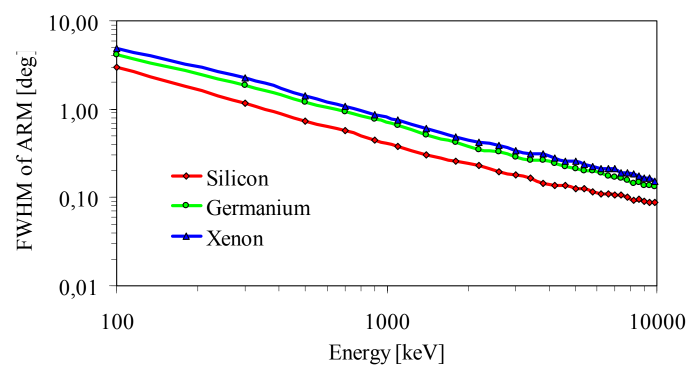


Energy and scatter angle dependence

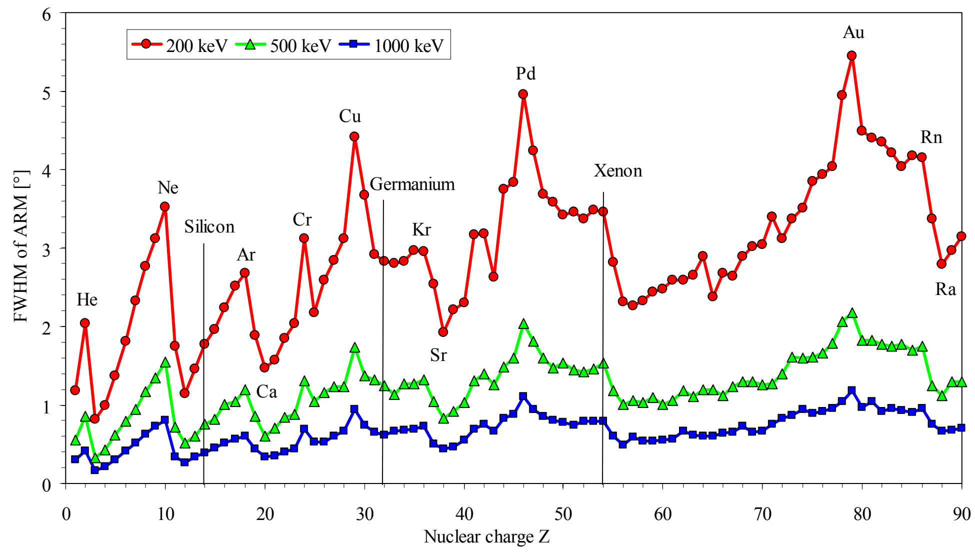


Left: Dependence of the angular resolution on the Compton scatter angle for germanium at four energies: The FWHM worsens with larger scatter angles and therefore with smaller energy of the scattered photon.

Right: Relationship between the initial photon energy and the angular resolution: On average silicon has a resolution roughly 1.6 times better than that of germanium and roughly 1.9 times than that of xenon. All three curves roughly fit a power law with an index of 0.75.



Nuclear charge dependence



This figure presents the dependence of the angular resolution on the nuclear charge. On average, the angular resolution worsens with increasing Z. But it also strongly depends on the shell structure of the individual atoms. Up to calcium (Z=20) the relationship is simple: the FWHM increases until it reaches a noble gas (He, Ne, Ar), then it decreases and reaches a minimum at the alkaline metals or alkaline earth metals. However, for higher atomic numbers the noble gases krypton, xenon and radon are only smaller local maxima. The three highest local maxima around Z=30, Z=46 and Z=79 are reached when the 3d, 4d and 5d orbitals are filled for the first time. For example, Pd-46 is the maximum, and not Cd-48, because of its special electron configuration: the two electrons from the 5s orbital are filling the 4d orbital. Similar reasons can be found for other extraordinary local maxima, e.g. for Cr-24 the 3d orbital is half filled.

Of the most important detector materials for next generation Compton telescopes, silicon has the best angular resolution assuming ideal detector properties, followed by germanium and finally the noble gas xenon. Nevertheless, from the Doppler broadening point of view a Compton telescope based on alkaline or alkaline earth metals would be the best choice. Since a modern Compton telescope scatter material should preferably be a semiconductor in order to get a high energy and spatial resolution, one possibility could be to use II-VI semiconductors. But there are two important drawbacks: Most of the II-VI semiconductors do not consist of alkaline earth metals but of transition elements with an appropriate electron configuration (CdTe), and materials like MgS suffer from their second compound: If one compares magnesium and sulfur with silicon, then the FWHM of sulfur is almost the same amount worse than silicon as magnesium is better than silicon. Furthermore, scintillators like NaI, which consist of a low-Z and a high-Z compound, are dominated by the high-Z material because of its larger number of electrons and can therefore not benefit from their alkaline metal component.

Material	Si	Ge	CdTe	Xe	Ne213	CsI	NaI
FWHM at 200 keV [°]	1.80	2.85	3.50	3.30	1.75	2.95	3.00
FWHM at 500 keV [°]	0.80	1.25	1.55	1.45	0.75	1.25	1.40
FWHM at 1000 keV [°]	0.40	0.65	0.85	0.80	0.40	0.75	0.85

Conclusions

Doppler broadening is a fundamental limit for the angular resolution of Compton scattering-based telescopes below roughly 1 MeV. Unfortunately, it invalidates several strategies to improve Compton telescopes at these energies:

Due to their stopping power high Z materials (e.g. Ge, CdTe, Xe) are favored in gamma-ray astronomy. They guarantee a high efficiency, but their angular resolution is fundamentally limited. In particular, germanium Compton telescopes cannot take advantage of their good energy resolution, since they have already reached their Doppler limit at lower energies.

From the Doppler broadening point of view a Compton telescope should be based on silicon since it can achieve the best angular resolution. But, on the other hand, silicon needs much more material to achieve the same efficiency and the energy resolution is worse than in germanium telescopes. Nevertheless, if in the future it becomes possible to substantially improve the energy resolution of silicon, the resolving power for close sources of a Si-based telescope could be better than that of a system based on germanium or other high-Z materials.

For Tracking Compton telescopes, the scatter angle dependence of the Doppler broadening seems to be a disadvantage, since an electron needs a certain amount of energy to pass through several layers of material. The required amount of electron energy corresponds to a bias towards larger scatter angles. But since a reasonable amount of tracking first sets in at roughly 1-2 MeV of the initial gamma-ray, and since those detectors are based on silicon, Doppler broadening in the current implementations is not a limiting factor.

Another drawback are the wide tails of the angular distributions. They represent additional background which has to be rejected by appropriate methods, and they make it more difficult to resolve sources in crowded fields, e.g. in the galactic center region.

At the moment no way is known to overcome the Doppler limit. Therefore below roughly 1 MeV Compton telescopes cannot give a better angular resolution than modern coded mask systems like IBIS on board INTEGRAL, which has an angular resolution of roughly 0.2°. Even an ideal silicon-based Compton telescope will not reach this value below 1-2 MeV, depending on the event selections.

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